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Aberdeen Proving Ground, MD

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Lifecycle Cost Assessment of Fuel Cell Technologies for Soldier Power System Applications

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The US Army Communications-Electronics Research Development and Engineering Center (CERDEC) Fuel Cell Technology Team has executed a series of development programs over the past several years examining fuel cell technologies for soldier power applications in the 15 to 100-Watt range. The focus of this program has been to demonstrate the feasibility and highlight the benefits of fuel cell systems in hybrid configurations and integrated into specific power applications. Although many technical objectives have been achieved, future procurement decisions will significantly depend on the price differential between various competing fuel cell technologies and the more traditionally used batteries. Recent improvements in the reliability and performance of Soldier power fuel cell systems have resulted in a new focus on future procurement and cost assessments. To date, there is no single source for cost and pricing information on Soldier fuel cell systems. CERDEC intends to focus on the near and long term cost of developing and fielding Soldier fuel cell systems. Surveys were submitted to multiple Soldier power fuel cell system integrators requesting cost data on complete systems and balance of plant components. Additionally, companies were asked to provide information on methods for recycling components and integrated system performance data. The surveys were directed toward system manufacturers who had previously developed and demonstrated a fuel cell power system in the 15 to 100-Watt range. These systems were chosen because they were viewed as the closest to being transitioned into military applications. Specific technologies under consideration include direct methanol fuel cells (DMFC), reformed methanol fuel cells (RMFC), and solid oxide fuel cells (SOFC).

15. SUBJECT TERMS
lifecycle cost assessment, fuel cell, soldier power

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Lifecycle Cost Assessment of Fuel Cell Technologies for Soldier Power System Applications

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Abstract: The US Army Communications-Electronics Research Development and Engineering Center (CERDEC) Fuel Cell Technology Team has executed a series of development programs over the past several years examining fuel cell technologies for soldier power applications in the 15 to 100-Watt range. The focus of this program has been to demonstrate the feasibility and highlight the benefits of fuel cell systems in hybrid configurations and integrated into specific power applications. Although many technical objectives have been achieved, future procurement decisions will significantly depend on the price differential between various competing fuel cell technologies and the more traditionally used batteries. Recent improvements in the reliability and performance of Soldier power fuel cell systems have resulted in a new focus on future procurement and cost assessments.

To date, there is no single source for cost and pricing information on Soldier fuel cell systems. CERDEC intends to focus on the near and long term cost of developing and fielding Soldier fuel cell systems. Surveys were submitted to multiple Soldier power fuel cell system integrators requesting cost data on complete systems and balance of plant components. Additionally, companies were asked to provide information on methods for recycling components and integrated system performance data. The surveys were directed toward system manufacturers who had previously developed and demonstrated a fuel cell power system in the 15 to 100-Watt range. These systems were chosen because they were viewed as the closest to being transitioned into military applications. Specific technologies under consideration include direct methanol fuel cells (DMFC), reformed methanol fuel cells (RMFC), and solid oxide fuel cells (SOFC).

A literature review of fuel cell technologies for Soldier power applications yielded few results with respect to cost modeling. A greater number of publications target stationary or transportation applications. However, these few relevant cost estimates from literature in combination with the cost and performance data generated through the survey allow a dollar-per-Watt and dollar-per-Watt-hour figure to be estimated for each technology over its lifecycle. These calculated cost estimates are applied to several key Soldier power applications (i.e. Soldier-worn and radio) to determine if any single technology is clearly more cost effective for a given mission over another. This paper offers a snapshot of Soldier power fuel cell system development progress and provides a comparison with current power solutions on a cost and functional basis.

Keywords: lifecycle cost assessment; fuel cell; soldier power

Introduction:

The US Army CERDEC Fuel Cell Technology Team has been evaluating fuel cell power sources in the 15 to 100-Watt range and developing these technologies with various commercial vendors for a quite some time [1], [2]. Fuel cell technologies in this power range have been targeted for the development of a hybrid power scheme (i.e. fuel, fuel cell, batteries, etc) which would enable a reduction in weight carried by the user in a given mission scenario. For the most part, the results of this effort have demonstrated improved gravimetric energy density (300 to 550 Watt-hours per kilogram), moderately reliable operation (hundreds of hours and tens of on / off cycles), and survivability in extreme operational environments (from -15 degrees Celsius up to >50 degrees Celsius) when applied to a 25-Watt, 72-hour mission application. The relative lifecycle costs of competing fuel cell technologies, as well as the fuel cell system cost compared to batteries currently in use for these missions, will become a significant factor for consideration as various fuel cells show themselves capable of meeting and exceeding these basic performance metrics.

No comprehensive, publicly-available source for lifecycle costs of portable fuel cell systems currently exists. Much of this information remains proprietary, since many of the developers working to commercialize these technologies are start-up companies with private capital investment. However, Fuel Cell Today recently claimed victory for commercialization of portable fuel cell systems during 2007 [3]. With the commercialization of portable fuel cells, one may expect that more information on costs will become available as commercial (i.e. emergency responder, leisure, etc) and military sales increase. A majority of the published data on the costs of fuel cell power systems relates to space, stationary, and 1 to 5 – kilo-Watt auxiliary power applications (i.e. telecom backup, forklift, etc), since these markets are either already well-established or offer significant near-term niche opportunities that have been detailed by Citigroup [4], and others. To the greatest extent possible, the US Army CERDEC has reviewed the publicly-available information for portable applications and has attempted to apply this knowledge to generate a dollar-per-Watt and dollar-per-Watt-hour figure for each of the major fuel cell technologies currently being considered.

The US Army CERDEC submitted cost surveys to a variety of portable fuel cell system developers in hopes of promoting greater sharing of cost data in the public domain. This exercise proved pre-mature, since many of the targeted contractors were unwilling to share the level of detail that was sought or even submit any information at all due to concerns over the release of their proprietary information. However, CERDEC combined this limited gathered data from companies willing to participate with cost data found in literature, and produced an early view of the comparative costs of competing portable fuel cell technologies. While this paper seems to be the first analysis of its kind for portable applications, CERDEC hopes that other researchers will attempt similar, more-comprehensive comparative analyses for other fuel cell technologies and applications in the future.

Literature Review:

Several key topics for cost modeling of fuel cell technologies were noted by an in-depth review of technical journal articles. Baratto et al [5] executed a thorough literature review of available cost factors for fuel cell technologies. They investigated a 5-kW solid oxide fuel cell power system that utilizes an integrated auto-thermal reformer to process diesel fuel into a hydrogen-rich reformate for auxiliary power unit (idling reduction) applications. The system performance was simulated using Aspen Plus and costs were modeled using various simplified correlations. A significant point was highlighted in the article: “normal procedures and factors used in plant cost estimation do not apply” when scaling-down cost factors for larger fuel cell power systems. This applies even more when scaling-down from multi-kilowatt applications to multi-watt systems. The authors of the article also observed that “the manufacturing cost can be decomposed in the bare cost of each component and fixed costs.” This information leads to the belief that given the difficulty of using simplified cost correlations for the small systems being considered here, a rigorous estimate of component costs cannot be easily accomplished.

The CERDEC has utilized cost data from the previously mentioned industry survey in addition to performance data based on testing conducted in our own labs at Fort Belvoir, VA to formulate the cost metrics reported here. Since materials, components, system designs, and production processes are in a constant state of development and change, and much of this cost data is neither publicly-available nor reliable, a rigorous engineering cost estimate has not been performed.

Battelle compiled and presented a very detailed cost assessment of hydrogen-fueled proton exchange membrane (PEM) fuel cell systems for Defense Logistics Agency (DLA) distribution center forklifts (and other) near-term applications at the 2007 Fuel Cell Seminar [6]. In this study, the authors reported that the total lifetime costs of PEM fuel cell systems for forklift applications exceed that of battery-powered and propane-powered systems for single-shift operations over a 15-year life. When the authors considered double-shift operations, however, the economics changed significantly and PEM fuel cell forklifts showed the lowest overall lifecycle costs compared to the two alternatives. This conclusion highlights an important consideration for any comparative cost analysis: that the economics can vary when multiple use rates are considered. While this is an extremely significant consideration, for this paper we have not investigated alternative power/use profiles in our analysis due to the fact that the current targeted applications for portable fuel cells vary widely.

Cost Modeling and Discussion:

In our cost models, a 25-Watt continuous, 8-hour-per-day mission is used as the basis for comparison over three characteristic (assumed) lifetimes: 1000 hours, 2000 hours, and 5000 hours. The model also assumes production of prototype quantities (<100 units per year) thus economies of scale, learning curve theory, and the implementation of cheap, efficient manufacturing methods are not accounted for in the model. This offers the best analysis of near term cost. Current fuel packaging schemes were used for each of the fuel types considered. In several cases, fuel could be packaged in a more efficient manner based on mission requirements, but optimal packaging efficiencies are not accounted for here.

Three fuel cell technologies are considered in this analysis: direct methanol fuel cells (DMFC), reformed methanol fuel cells (RMFC), and solid oxide fuel cells (SOFC). These technologies are compared with each other and with military-standard lithium-manganese dioxide primary batteries. These technologies have been demonstrated at a more advanced technical maturity than other fuel cell technologies currently under development (such as PEM fuel cells with chemical hydrides). Metal hydrides with PEM fuel cells, although they represent one of the most mature and potentially cheapest portable power options over the lifecycle, are not considered for military applications due to significantly lower gravimetric energy densities compared to currently-used batteries. Other fuel cell technologies, such as alkaline fuel cells, lack maturity but could offer lower lifecycle costs due to relatively cheap materials of construction. Ovonic Fuel Cell Company [7] and others are demonstrating cost benefits at higher power levels (1.5-kW) with hydrogen fuel, but the ability to scale down these cost benefits to portable applications with use of packaged fuels remains to be seen.

The SOFC system under consideration is manufactured by Adaptive Materials Incorporated of Ann Arbor, MI. These systems were delivered to the CERDEC recently for test and evaluation, and have demonstrated 11.9 grams-per-hour fuel consumption at the rated 25-Watt load on commercially-available propane fuel. A generalized process flow diagram (PFD) for the system is provided in Figure 1.

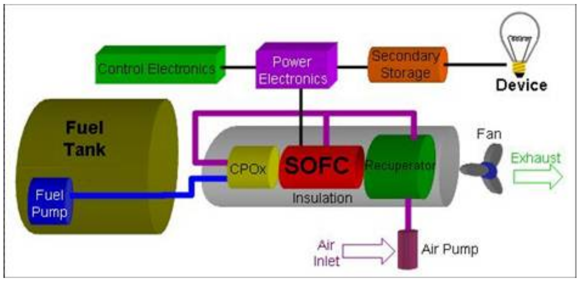

Figure 1 - Process flow diagram for a portable solid oxide fuel cell (SOFC) system, provided by Adaptive Materials Inc

The RMFC system (Figure 2) reported here is manufactured by Ultracell Corporation of Livermore, CA. This system has been tested extensively by CERDEC and has demonstrated 26.6 grams-per-hour fuel consumption at 25-Watts using a 67 % methanol / water fuel mixture.

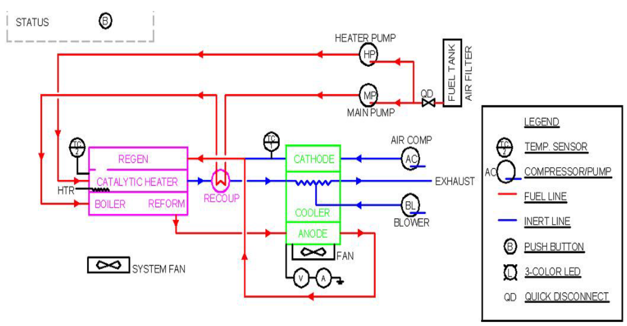

Figure 2 - Process flow diagram for a portable reformed methanol fuel cell (RMFC) system, provided by Ultracell Corp

The DMFC presented in this report is manufactured by Smart Fuel Cell of Brunnthal-Nord, Germany. Over several years, the company has demonstrated 17.3 grams-per-hour fuel consumption at 25-Watts using neat methanol fuel. A representative PFD [8] for the technology appears in Figure 3. Additionally, Table 1 displays the cost and performance data for a standard military BA-5390 battery, which was chosen for this analysis due to its low-cost, wide availability, and high capacity [9].

There are several important assumptions that were made while conducting this cost analysis. First, end-of-life costs were not considered for any technology, despite the fact that platinum [10] and Nafion [11] recycling technologies are under development with promising results. Second, our model does not include cost factors for shipment or disposal, as these metrics may inflate the lifecycle cost benefits of fuel cell technologies. Given the current state of development and information available, these costs would be near impossible to estimate and were therefore not included.

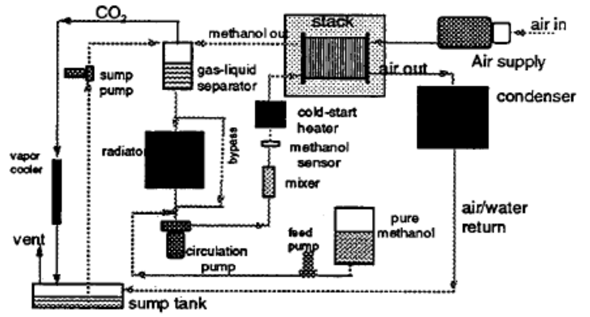

Figure 3 - Process flow diagram for a portable direct methanol fuel cell (DMFC) system

Table 1 - BA-5390 Data

BA-5390 Performance and Cost	
280	W-hr
1.36	Kg
11.2	hr @ 25W
$90	per unit

Third, although the analysis is completed for 1000, 2000, and 5000 hour lifetime profiles, none of the fuel cell technologies have demonstrated this total system lifetime, and are therefore all considered equivalent in terms of system life expectancy. Finally, depreciation and inflation are not considered in this simplified economic study.

Table 2 displays the results of the cost survey submitted to the portable fuel cell manufacturers. The table also includes cartridge fuel content for each technology. The cartridge cost for DMFC is assumed equivalent to that of RMFC since the cartridge compositions are very similar and DMFC cartridge cost information was not available.

Table 2 - System and cartridge costs provided by fuel cell system manufacturers

Technology	System Cost	Cartridge Cost	Cartridge Content
	$	*$*	*g*
DMFC	$3,146.00	$27.00	277
RMFC	$2,500.00	$27.00	218
SOFC	$5,000.00	$2.50	465

In addition to fuel and system costs, SOFC also requires the inclusion of a sulfur trap to prevent odorants present in commercial propane from contaminating the reforming and electro- catalysts. AMI estimates this cost at $200 for a 1000-hour sulfur trap, but claims this cost could go down drastically with increased sales volume. Figure 4 displays results of the overall lifecycle costs analysis for each of the assumed lifetime profiles. It can clearly be seen that all fuel cell technologies are far cheaper than currently used batteries, with DMFC as the cheapest option for the 1000-

hour profile ($4847) and SOFC as the cheapest for 2000 hours ($5527) and 5000 hours ($6320). Over shorter mission profiles, such as that for 1000-hours, it seems system capital cost becomes more significant. It is clear for longer missions that fuel cartridge cost has a significant effect on lifecycle costs, thus high-energy-density fuels such as commercially-available propane seem most favorable in this analysis. Figures 5 and 6 display the same results on dollar-per-Watt and dollar-per-Watt-hour bases. It is particularly interest to note the decreasing $/W-hr trend for all fuel cell technologies compared to the increasing trend for batteries as mission length increases. This is likely due to the re-usability of the fuel cell system, whereas the primary batteries considered here cannot be reused.

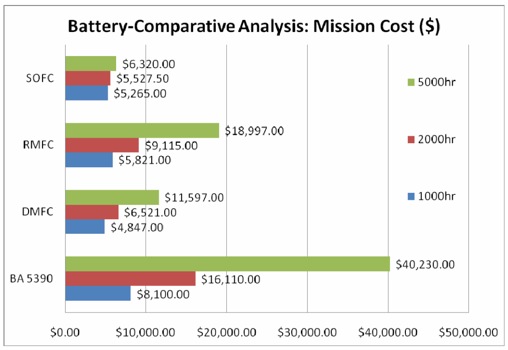

Figure 4 - Mission costs ($)

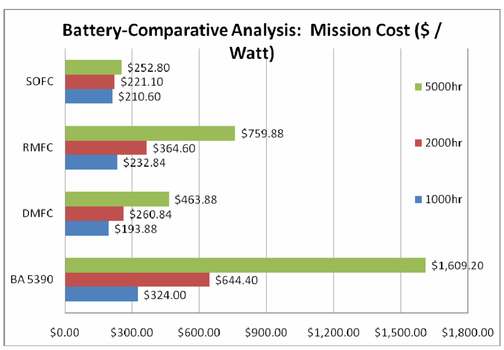

Figure 5 - Mission costs ($/W)

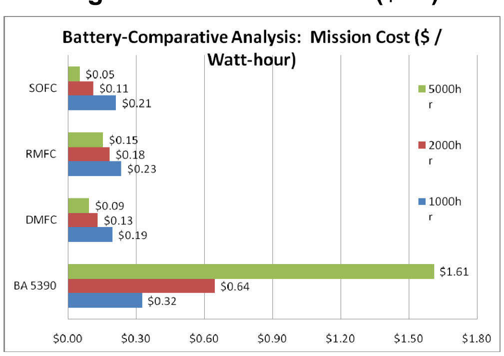

Figure 6 - Mission costs ($/W-hr)

Conclusion:

Lifecycle costs of portable fuel cell systems are not widely available in the public domain. This paper attempts to demonstrate some of the lifecycle cost benefits that are possible with portable fuel cell systems as capital costs of systems and fuel cartridges decrease and availability and reliability increase. Costs of portable fuel cells over their lifecycle are clearly dominated by the cost of fuel, thus future reductions in fuel cost will ultimately result in lower ownership costs.

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RDECOM

Life-Cycle Cost Assessment of Fuel Cell Technologies for Soldier Power System Applications

Power Sources Conference
09 July 2008

CERDEC
US ARMY – RDECOM

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Jonathan M. Cristiani, CERDEC Fuel Cell Technology Team

Who We Are

Department of Defense (DoD)

Department of the Army (DA)

Army Materiel Command (AMC)

Research, Development and Engineering Command (RDECOM)

Communications-Electronics Research, Development and Engineering Center (CERDEC)

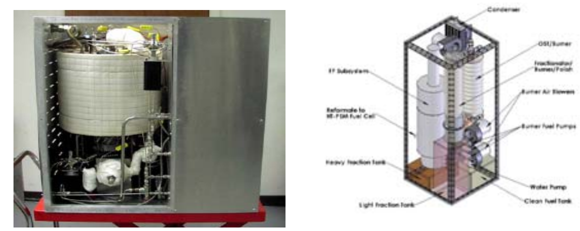
Command and Control Directorate (C2D)

Army Power Division

>$60M/YR Execution
6.2 + 6.3 Power & Energy
Research & Development

Fuel Cell R&D
Mission Focus Areas





Soldier & Sensor Power (1W-100W)	Man-Portable Power (100W-500W)	Auxiliary Power Units (500W-10kW)



Mission: Rapidly develop and transition suitable fuel cell technologies to applications where they are most needed.

Army Power Division
Transition and Support

Customers

Partners

Fuel Cell Industry & Academic Partners

AMI
Adaptive Materials Inc.

UltraCell™
HIGH POWER MICRO FUEL CELLS

SFC
Smart Fuel Cell

jadoo
Power

GENERAL ATOMICS

EBA&D
Ensign-Bickford Aerospace & Defense Company

LYNNTECH

ULTRALIFE® Batteries

Giner Electrochemical Systems, LLC

Protonex™

ASPEN PRODUCTS GROUP, INC.

IdaTech®

CGFCC
INNOVATION MADE SIMPLE

NanoDynamics Inc

Tennessee Tech University

RADIAN
ENGINEERING · LOGISTICS · SECURITY

ESSI
Engineered Support Systems, Inc.

Altex Technologies Corporation

Precision Combustion, Inc.

THE UNIVERSITY OF TOLEDO
1872

Need for LCCA

- LCCA is cornerstone to any acquisition program
- No existing data in public domain for lifecycle cost of various portable fuel cell systems
- Literature review shows most focus on 1-5 kWe pure-hydrogen PEMFC or SOFC systems
  - Baratto et al, Journal of Power Sources
  - Citigroup, Dist. Telecom Backup
  - Battelle, Fuel Cell Seminar 2007
- Fuel Cell Today: “Commercialization of fuel cells occurred in 2007” for portable applications

Survey Instrument

- Cost surveys submitted to 10 portable fuel cell OEMs in January 2008
- Responses from 3 companies
- Lack of responses from other companies due to protection of proprietary information
- Future LCCA to include other technologies such as sodium borohydride and ammonia borane fueled PEMFC and alkaline fuel cells, as they are further developed

Assumptions

- 25-watt, 8-hours per day continuous mission
- Characteristic lifetimes assumed for ALL technologies: 1000, 2000, 5000 hours (none of which have been demonstrated in CERDEC labs by a portable fuel cell technology to-date)
- Current fuel packaging schemes (not optimized)
- No end-of-life costs (disposal, recycling, etc)
- Transportation costs not considered
- Depreciation and inflation not considered
- Cost of methanol for RMFC and DMFC assumed same, although RMFC uses 67% methanol and DMFC uses neat methanol

Battery System Cost

BA-5390 Performance and Cost	
280	W-hr
1.36	Kg
11.2	hr @ 25W
$90	per unit

Fuel Cell System Cost

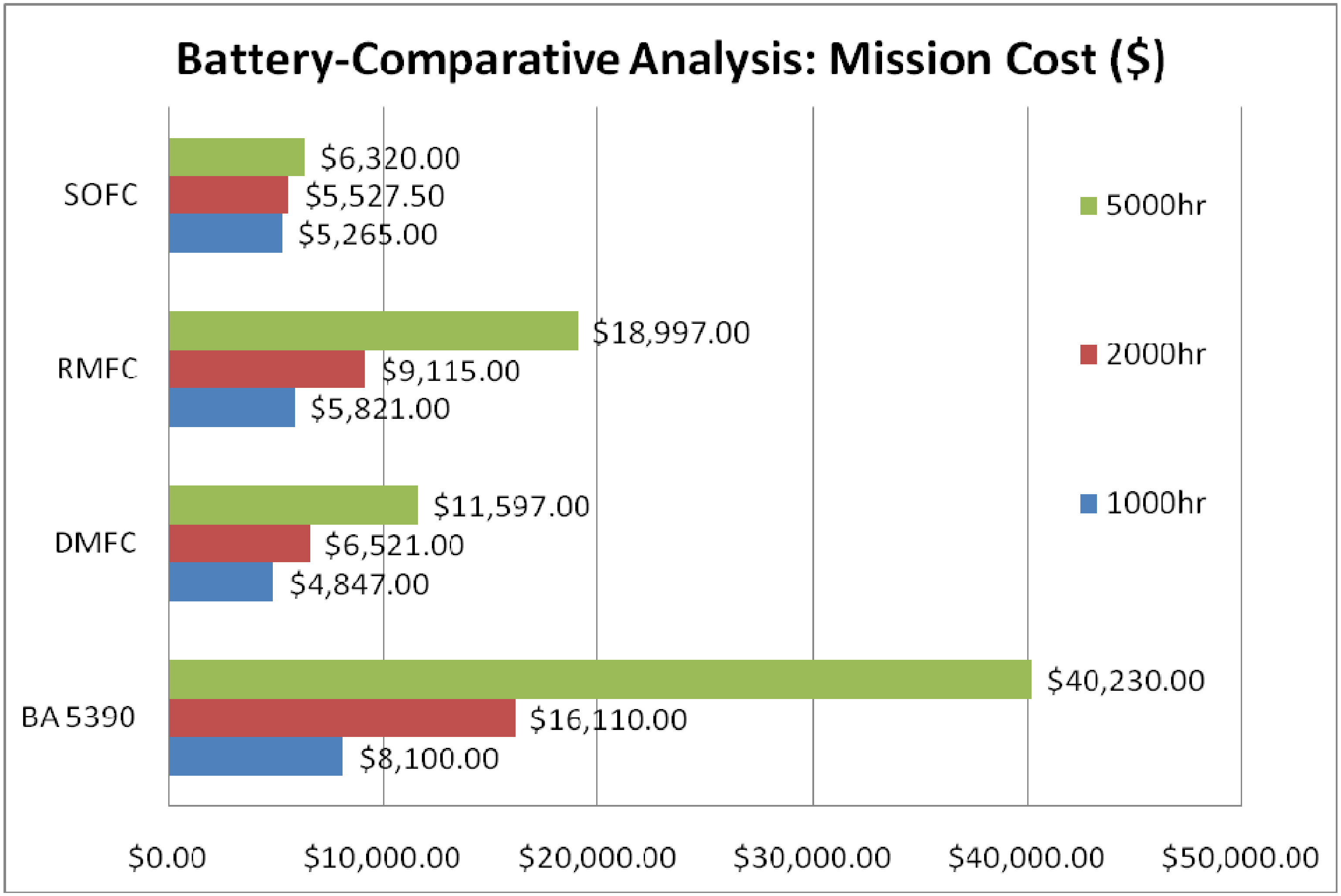
Technology	System Cost	Cartridge Cost	Cartridge Content
	$	*$*	*g*
DMFC	$3,146.00	$27.00	277
RMFC	$2,500.00	$27.00	218
SOFC	$5,000.00	$2.50	465

Pricing based on low rate commercial quantities (100's per year)

RMFC Cost with Various Cartridge Sizes

Technology	System Cost	Cartridge Cost	Cartridge Content
	$	*$*	*G*
RMFC 250 cc	$2,500.00	$27.00	218
RMFC 1-gal	$2,500.00	$150.00	3301
RMFC 5-gal	$2,500.00	$300.00	16,505

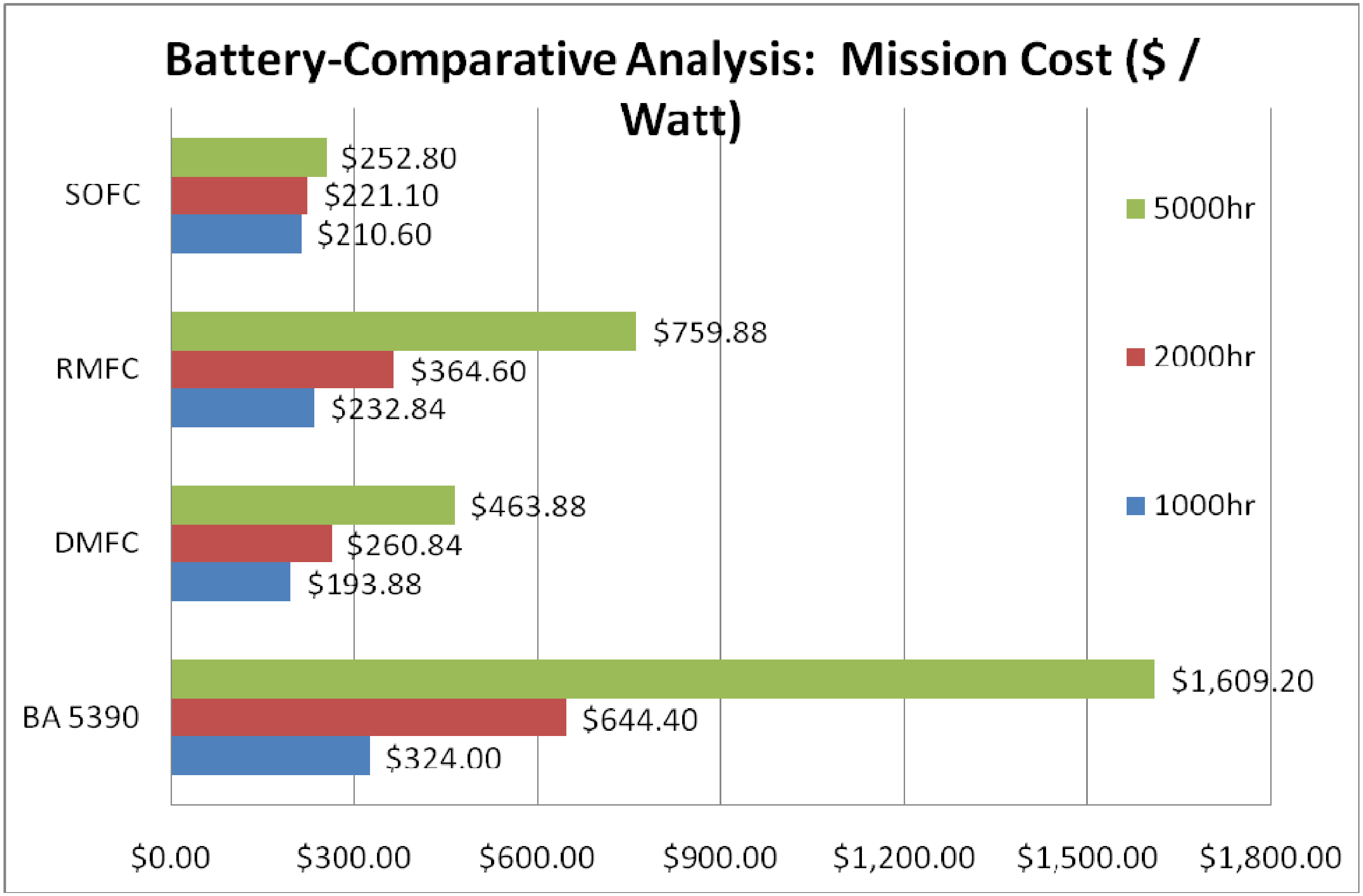
Mission Cost ($)



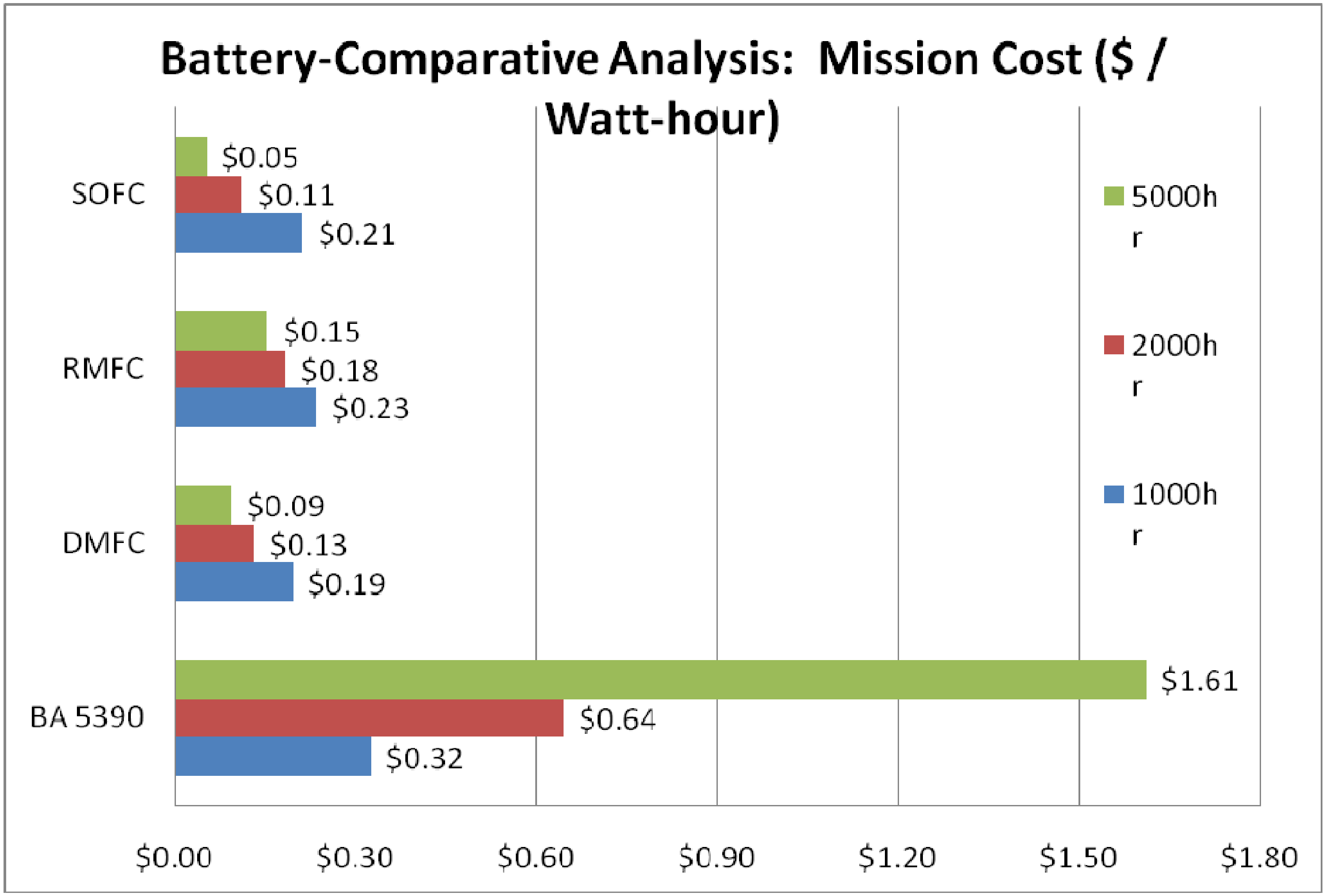
RMFC LCC with Various Cartridge Sizes

Technology	LCC for 5000-hr Life
	$
RMFC 250 cc	$18,997.00
RMFC 1-gal	$8650.00
RMFC 5-gal	$4900.00

Mission Cost ($/W)



Mission Cost ($/Whr)



Conclusions

- Fuel cells more economical than batteries for all three lifetime profiles examined
- Current pricing with smallest cartridges shows DMFC has lowest cost for 1000-hour lifetime with SOFC most economical for 2000-hour and 5000-hour lifetimes
- Commercial availability and high energy density of propane fuel results in lowest life cycle costs as lifetime increases
- Cost of fuel cartridge dominates fuel cell ownership costs as lifetime increases, capital cost more important factor for shorter lifetimes